RCS of a F-35 Stealth Aircraft: Statistical Analyses of a POFACETS Model

Fausta Mattei
Department of Industrial Engineering
University of Naples "Federico II"
Napoli, Italy
fausta.mattei@unina.it

Luca Pallotta
Department of Engineering
University of Basilicata
Potenza, Italy
luca.pallotta@unibas.it

Domenico Accardo
Department of Industrial Engineering
University of Naples "Federico II"
Napoli, Italy
domenico.accardo@unina.it

Antonio De Maio
Department of Electrical Eng. and Inf. Tech.
University of Naples "Federico II"
Napoli, Italy
ademaio@unina.it

***Abstract*—This paper analyzes the simulated radar cross section (RCS) of the POFACETS F-35 aircraft model versus azimuth and elevation aspect angle. In particular, the RCS values are obtained for all azimuths and for a short-range (SR) elevation regime. Moreover, the tests are conducted considering three different frequencies of the transmitted wave, viz. 0.3 GHz (VHF), 1 GHz (L), and 10 GHz (X). The RCS data for the F-35 aircraft are derived through a realistic model implemented in the Mathworks Matlab simulation toolbox POFACETS, developed at the Naval Postgraduate School of the USN. Therefore, a statistical analysis of the simulated RCSs is performed to establish among which is the best theoretical model representing these data. In this respect, the parameters for the theoretical distribution are selected using the moment matching technique. Then, the best fit statistical distribution is selected as the one minimizing the Cramèr-von Mises (CVM) distance from the empirical one. Finally, the spatial autocorrelation function is also derived to evaluate the degree of spatial decorrelation under each elevation regime and operative frequency.**

***Index Terms*—radar cross section (RCS), F-35 aircraft, statistical analyses, moment matching.**

I. Introduction

The most investigated parameter when dealing with radar target detection is surely the radar cross section (RCS), which describes the capability of a target to scatter electromagnetic (EM) waves and, consequently, of being intercepted [1]–[3]. Hence, to reduce the probability of being detected, a target should be designed such that its RCS is as low as possible. Several studies have been conducted in this direction, especially in military contexts, where the stealth technology (ST) (or low observable targets) has become a key concept [4]. Being the RCS depending on geometry, material composition, radar aspect angle, target angular orientation, frequency, and polarization [1], [2], passive ST essentially exploits two of these concepts to minimize the RCS, viz., the geometry of the object and the use of radar absorbing materials (RAM) [5], that allow to reduce the amount of the backscattered EM energy. Undoubtedly, among the most popular stealth aircraft there is the F-35 developed by Lockheed Martin [6]. In fact, a lot of research and studies on the F-35 are in continuous development, with the realization of simulation computer aided design (CAD) models of the F-35 and the evaluation of its RCS under different frequency/polarization conditions of the impinging EM wave. The interested readers may refer to [7]–[10] to deepen. It is also worth mentioning reference [11], where an interesting analysis in the S-band of the RCS for the F-22 CAD model (whose shape and size are close to those of the F-35) is provided, showing pros and cons of using such simulated models for RCS evaluation.

Beyond collecting data, however, the analysis of these RCSs is essential to designing radar receivers sensible enough to indicate the presence of such stealth-type targets as well as to accurately predict the performance of detection algorithms. In this context, this paper presents a statistical analysis of the RCS signatures for the F-35 aircraft POFACETS model under a short-range (SR) elevation aspect angle regime, with a radar operating in three frequency bands, i.e., VHF, L, and X. In this paper, we make use of the Mathworks Matlab simulation toolbox POFACETS, developed at the Naval Postgraduate School of the University of Southern California (USN), for RCS calculations [12], [13]. The software is an implementation of the physical optics approximation for predicting the RCS of complex objects, whose shapes are built by means of triangular facets, each with its own reflecting characteristics. Therefore, a detailed first-order statistical analysis of the measured RCSs of the F-35 aircraft for varying azimuth/elevation angles is performed by fitting the simulated data with mono- and bi-parametric distributions typically employed to model amplitude fluctuations [3], [14], [15]. This is done by resorting to the minimization of the Cramèr-von Mises (CVM) distance between the theoretical and empirical cumulative distribution function (CDF)s. Additionally, the spatial autocorrelation of the RCS vs view angles is also employed to further study the angular decorrelation behavior of the simulated RCS data.

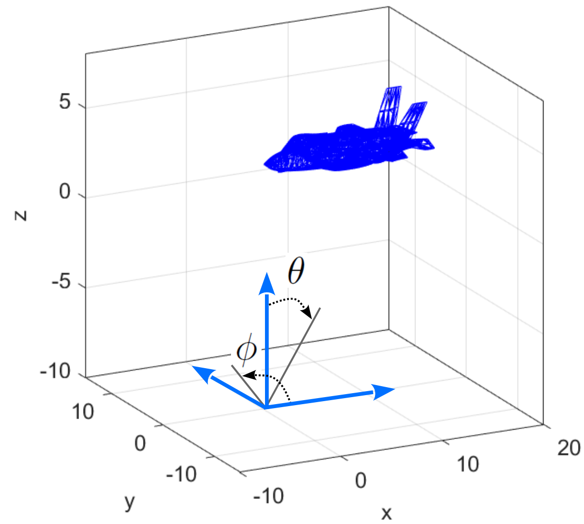
The organization of the paper is the following. In Section II, the procedure used to derive the data is described and the methodology for the statistical analyses is described. The results on simulated RCS data are then provided in Section III. Finally, Section IV summarizes the main contribution of this paper and gives some hints for possible future works.

II. RCS STATISTICAL BEHAVIOR OF F-35 AIRCRAFT

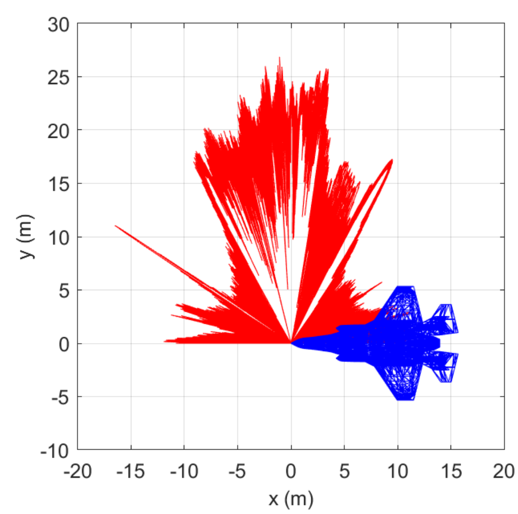
The traditional method of assessing radar detection performance relies on the premise that the RCS of the target follows one of the Swerling models I-V [3]. Nevertheless, some examples of practical application have shown that amplitude fluctuations are not always consistent with the above models, which can lead to discrepancies between the real-world radar performance and the theoretical one. In the open literature, several alternative parametric fluctuation models have been proposed to address this issue, including Weibull, Log-normal, K, and so on [3], [16]. Radar detection performance can be accurately predicted if the statistical behavior of the RCS is properly described. To do this, in the present section, a statistical analysis of the simulated RCS signatures of the F-35 aircraft is performed by fitting simulated data with known and commonly used (mono and bi-parametric) distributions over various aspect angles and at some frequencies of wide interest. Subsequently, the most suitable statistical model is selected as the one whose theoretical distribution minimizes the CVM distance from the empirical CDF of the F-35 RCS data (extracted in the azimuth/elevation angle domain).

A. F-35 RCS Data

In this section, a description of the simulation setting involved in the computation of the RCS data of the F-35 aircraft is given together with that of the data used in the next statistical analyses. As already described, the data are generated through the Mathworks Matlab simulation toolbox POFACETS v4.5 [12], [13]. The software is an implementation of the physical optics approximation for predicting the RCS of complex objects, whose shapes are built by means of triangular facets each with its own reflecting characteristics. In particular, the object is provided with the toolbox as a predefined model, whose shape is approximately realized by arrays of triangles (facets). Each facet can be either illuminated by one or two sides, depending on its illumination property. Moreover, a resistivity (whose value is normalized to that of free space equal to 377 Ω) is also associated with each facet. The model for the F-35 provided by the POFACETS is illustrated in Fig. 1, where subplot (a) shows the used reference system emphasizing the azimuth ϕ and elevation θ angles, and subplot (b) shows the x-y view-plane (i.e., the plane for $\theta = 90$ deg). Hence, the RCS for the F-35 is computed for a monostatic radar with the scattered field evaluated for each triangle alone excluding all multiple reflection and diffraction effects. During simulations, the RCSs are computed setting the polarization of the incident wave to be a pure transverse mode (TM). As to the considered aspect angle, the data are elaborated for the azimuth angle ϕ varying in the interval $[0, 180]$ deg (only one half is considered for symmetry), with a step size equal to 0.1 deg. Then, the elevation angle θ is set in order to comply with a range regime referred to as SR [8], for which $\theta \in [120, 122]$ deg, as graphically shown in Fig. 2. Finally, data are generated for a transmitted wave at three different frequencies, viz. 0.3 GHz (VHF-band), 1 GHz (L-band), and 10 GHz (X-band). The resulting RCS for the SR regime with an operating frequency of 10 GHz (X-band) is also shown overlapped to the target with a polar plot in Fig. 1(b).



(a)



(b)

Fig. 1. Reference system (subplot a) and x-y view (subplot b) of the F-35 with overlapped the polar plot of its RCS (dBsm), i.e., for elevation angle varying in the interval $[120, 122]$ deg, and in X-band (operating frequency 10 GHz).

To better understand the RCS behavior as a function of viewing angle, Fig. 3 shows the RCS results calculated for the F-35 aircraft with the three different operating frequencies and under the considered range regime. Beyond the curves representing the RCS data computed for each aspect angle

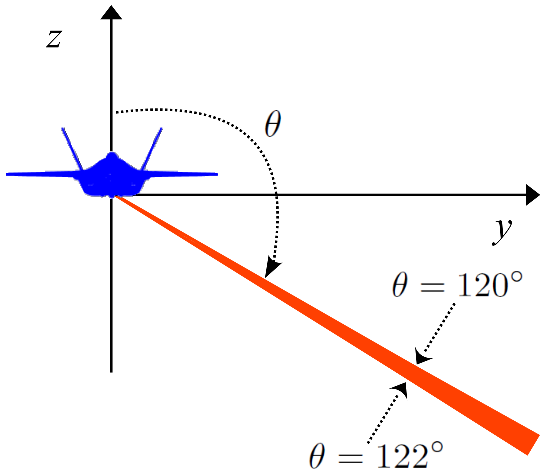
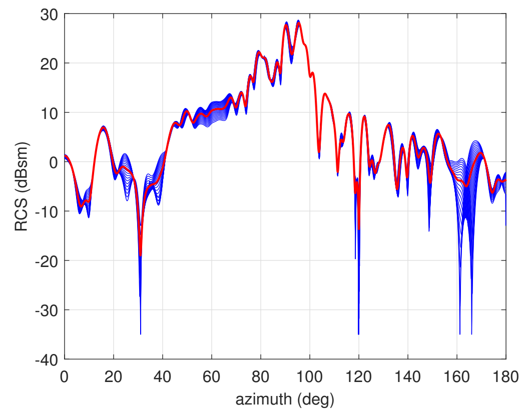


Fig. 2. Pictorial illustration of the SR elevation view angle, i.e., $\theta \in [120, 122]$ deg, in the considered reference system.

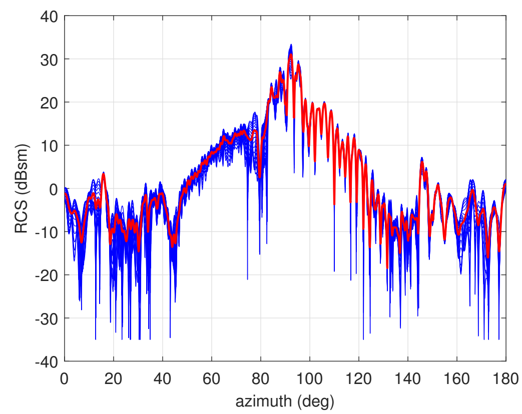
(blue curves), the mean value with respect to the elevation is also plotted (red curve). As expected, as the frequency of the transmitted EM wave grows, an increasingly oscillatory behavior of RCS values is observed. Moreover, the higher oscillations produce larger peaks in the corresponding diagram. It is, however, worth underscoring that the RCS is evaluated without accounting for RAM covering the F-35 surface. As a consequence, in the direction $\phi = 180$ deg, the RCS can assume values up to a few dBsm that are at least 10 dB higher than those expected in a real-world application. Note that, to overcome this drawback, in [9], the model for the F-35 has been changed removing the aircraft nose to emulate the transparency in terms of RCS. Moreover, it is interesting to observe that at a lower frequency (i.e., VHF) due to Rayleigh scattering the stealth capabilities of the target significantly reduce and the radar is facilitated to reveal it. As a matter of fact, the RCSs in the subplots (a) and (b) of Fig. 3 are on average higher than the others.

B. Statistical analyses by moment matching

This subsection is devoted to providing a methodology, that in line with [14], [16], allows to statistically characterize the RCS data for the F-35 aircraft described in the previous subsection. The focus is on the first-order statistical analysis aimed at deriving the best model representing the fluctuation of the F-35 data with respect to the view angle. The focus is on the CDF of $\sqrt{\sigma}$, with results confirming the deviations of the data from mono-parametric distributions like a Rayleigh model in favor of bi-parametric distributions. So, the empirical CDF (ECDF) is compared with five theoretic models from the literature generally used to describe the amplitude CDF, viz. Rayleigh, K, Weibull, Gamma, and Log-Normal [17], whose parameters are estimated from the data through a moment matching. Table I summarizes the analytic expression of the above described CDF also indicating their related parameters. Note that, the functions $\Gamma(\cdot)$, $\gamma(\cdot,\cdot)$, and $\mathrm{erf}(\cdot)$ in the table



(a)



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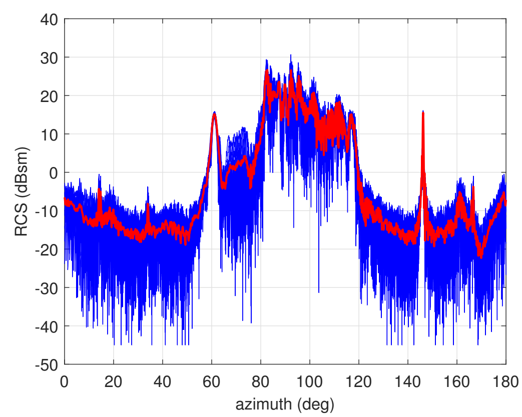


(c)

Fig. 3. RCSs (dBsm) (blue line) and its mean value (red line) versus azimuth (in degrees) of the F-35 aircraft, for the three considered frequency band (i.e., VHF, L, and X, from top to bottom) under the SR regime.

denote the Gamma, the incomplete Gamma, and the error functions, respectively.

Finally, the theoretical model that provides the best fit respect to the data is selected as the one minimizing an integral distributional distance between the designed CDF

TABLE I
THEORETICAL CDF AND THEIR PARAMETERS

distribution	CDF	parameters		support
Rayleigh	$F(x;b^2) = 1-\exp\left(-\frac{x^2}{2b^2}\right)$	$b^2 < 0$		$x \geq 0$
K	$F(x;\mu,\nu) = 1-\frac{1}{2^{\nu-1}\Gamma(\nu)}\left(\sqrt{\frac{2\nu}{\mu}}\right)^{\nu} K_\nu\left(\sqrt{\frac{2\nu}{\mu}}x\right)$	$\mu > 0$ (scale)	$\nu > 0$ (shape)	$x \geq 0$
Weibull	$F(x;\mu,\nu) = 1-\exp\left[-\left(\frac{x}{\mu}\right)^{\nu}\right]$	$\mu > 0$ (scale)	$\nu > 0$ (shape)	$x \geq 0$
Gamma	$F(x;\mu,\nu) = \frac{1}{\Gamma(\nu)}\gamma\left(\nu,\frac{x}{\mu}\right)$	$\mu > 0$ (scale)	$\nu > 0$ (shape)	$x \geq 0$
Log-Normal	$F(x;\mu,\nu) = \frac{1}{2}+\frac{1}{2}\text{erf}\left(\frac{\log(x)-\mu}{\sqrt{2}s}\right)$	$\mu \in (-\infty,+\infty)$	$s > 0$	$x > 0$

and the ECDF, referred to as the CVM distance [18]. More precisely, denoting as $\sigma_1, \sigma_2, \ldots, \sigma_N$ the set of RCS values, the CVM distance between the design distribution $F(\sqrt{\sigma})$ and its empirical counterpart can be computed as

$$d^2 = \frac{1}{12N} + \sum_{i=1}^{N}\left|F(\sqrt{\sigma_{(i)}}) - \frac{2i-1}{2N}\right|^2, \tag{1}$$

where $\sigma_{(i)}$ denotes the i-th ordered statistic from the above set of RCSs.

III. RESULTS

In this section, the results of the analyses described in Section II on simulated F-35 RCS data are discussed. To this end, Fig. 4 shows the theoretical CDF for the five considered models whose parameters (see Table I) are estimated from the available data, together with their ECDF. The figure is organized into three subplots that refer to the above defined VHF-, L-, and X-bands (observing the figure from top to bottom) and under the SR regime. From a visual inspection of the figure it is evident that the data strongly deviate from the Rayleigh distribution, rather a bi-parametric model can better describe their statistical behavior. More specifically, using the criterion based on CVM distance the Log-Normal and Weibull distributions are chosen as the best fitting models. More precisely, the Log-Normal is chosen as the minimum distance distribution in the VHF-band, whereas the Weibull is chosen in the L- and X-band cases. These results are summarized in Table II, where the estimated values for the fitted distribution parameters are also reported. Interestingly, for the Log-Normal distribution the parameter μ (which is the mean value of the logarithm of the variable) is equal to about 0.65, whereas s (i.e., the standard deviation of the logarithm of the variable) is close to 1. Similarly, the scale parameter of the Weibull is about 1.9 in the L-band scenario and about 1.12 in the X-band, whereas its shape is about 0.60 and 0.56 in the L- and X-band, respectively.

Before concluding this study about the F-35 aircraft RCS, the spatial decorrelation behavior is also studied as the operating frequency varying as well as for the considered elevation aspect angle regime. Precisely, indicating with L_w the length expressed in meters, the spatial (angular) decorrelation can be evaluated as [3]

TABLE II
BEST FIT THEORETICAL CDF AND THEIR PARAMETERS OF THE RCS DATA FOR THE SCENARIOS OF FIG. 4.

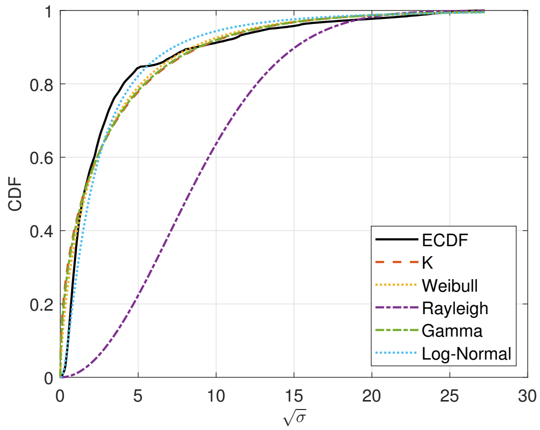
scenario	selected CDF	estimated parameters	
VHF-SR	Log-Normal	$\hat{\mu} = 0.6502$	$\hat{s} = 1.0410$
L-SR	Weibull	$\hat{\mu} = 1.8761$	$\hat{\nu} = 0.5960$
X-SR	Weibull	$\hat{\mu} = 1.1171$	$\hat{\nu} = 0.5630$

$$\Delta\theta_d = \frac{c}{2L_w f_0}, \tag{2}$$

where $c = 3\times10^8$ m/s is the speed of light and f_0 is the carrier operative frequency. For the F-35 aircraft herein considered, its size is 15.7 m in the x-direction and 10.7 m in the y-direction [6], therefore a minimum and maximum spatial autocorrelation can be derived, respectively. The resulting values for the spatial autocorrelation (averaged over elevation) are plotted in Fig. 5, where the angle at which the spatial decorrelation occurs according to (2) is also plotted as a vertical bar. From figure inspection, the evidence is that as the frequency increases, there is a narrowing of the autocorrelation mainlobe. Certainly, the RCS of the F-35 has the tendency to decorrelate the faster the higher is the observation frequency. Therefore, in the X-band even very small changes in the angle of view lead to significant changes in the RCS, such that they could lead to detection losses by the radar.

IV. CONCLUDING REMARKS

In this paper a study of the RCS of the F-35 aircraft has been conducted. Firstly, data are obtained by simulation through the use of the Matlab toolbox POFACETS, which exploits the physical optics to compute the RCS. Hence, data are generated for all azimuth angles and several elevations, also assuming three different operating frequencies. Then, intensive statistical analyses of the available RCSs have been performed. They consisted in searching for the theoretical CDF that best fitted the empirical one, using the moment matching technique to estimate the distribution parameters and the CVM distance to evaluate the goodness of fitting. Interestingly, the Weibull distribution resulted to almost always show the best fit. Finally,



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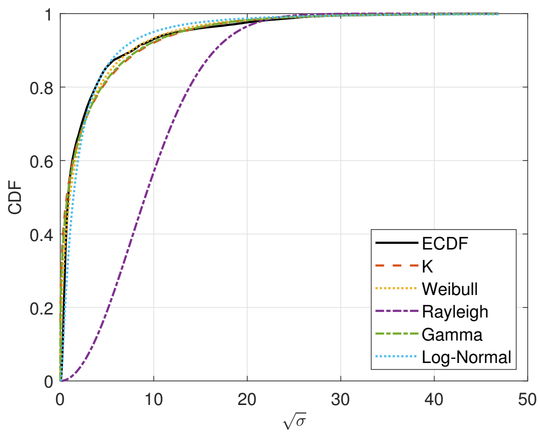

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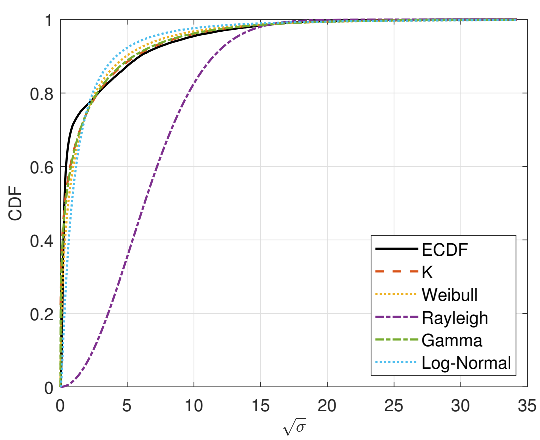

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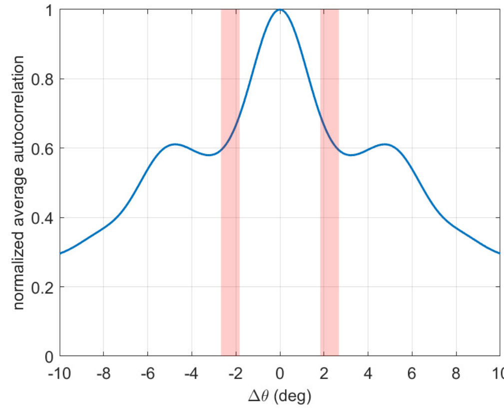
Fig. 4. Theoretical CDF and ECDF versus $\sqrt{\sigma}$ of the F-35 aircraft, for the three considered frequency bands (i.e., VHF, L, and X, from top to bottom) under the SR regime.



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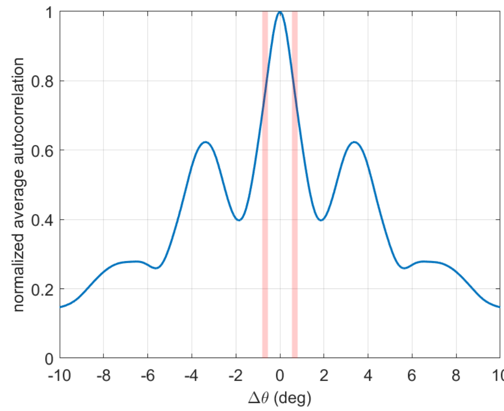

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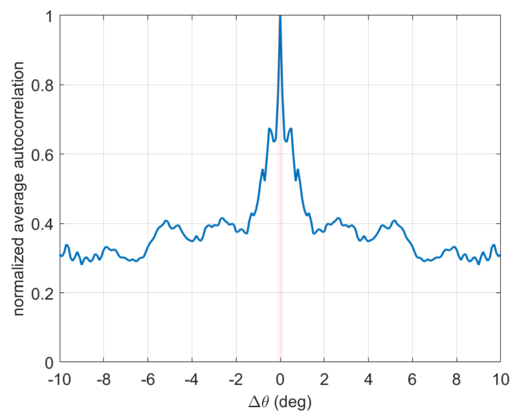

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Fig. 5. Normalized average autocorrelation of the RCS of the F-35 aircraft, for the three considered frequency bands (i.e., VHF, L, and X, from top to bottom) under the SR regime.

the spatial decorrelation has also been evaluated, showing a very rapid decorrelation of the RCS, especially at X-band.

Future works could consider the prediction of the detection performance for a radar system when the F-35 RCS are modeled as indicated by the performed statistical analysis.

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